# Gluon Saturation Effects in Exclusive Heavy Vector Meson Production

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Based on 2411.14815

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SURGE collaboration

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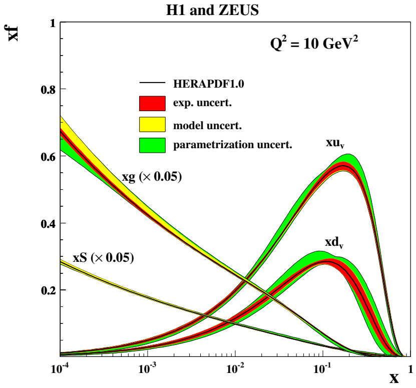
# Gluon saturation at high energy

- HERA: rapid growth of gluon distribution at small $x$
- Growth cannot go on indefinitely: violation of unitarity
- Will eventually be tamed by gluon recombination effects
- Prediction from theory: **gluon saturation**
- Signs of saturation in the experimental data but no definite evidence




H1 and ZEUS (0911.0884)

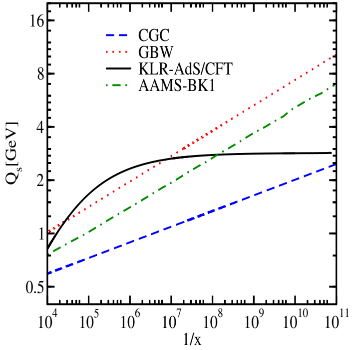
# Searching for saturation

- Saturation effects characterized by the **saturation scale** $Q_s^2$
- For saturation to be important:

  Momentum scale in the process has to be comparable to $Q_s^2$
- However: $Q_s^2$ is quite small...
  - Protons: $Q_{s,p}^2 = \mathcal{O}(1\,\mathrm{GeV})$
  - Nuclei: $Q_{s,A}^2 \sim A^{1/3} Q_{s,p}^2$

    $\Rightarrow$ Nuclear enhancement of saturation!
- Energy dependence: $Q_s^2 \sim 1/x^{0.3}$
- Search for saturation:

  Need a high energy (small $x$) and a low momentum scale




Rezaeian (1001.5266)

# Exclusive vector meson production

Ryskin, Z.Phys.C 57 (1993) 89-92

$$\frac{\mathrm{d}}{\mathrm{d}t}\sigma(\gamma^* + A \to V + A) \sim [xg(x)]^2$$

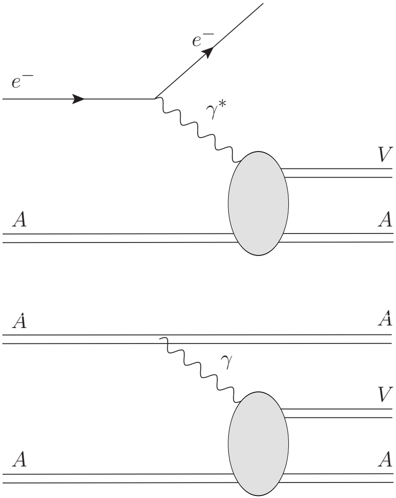
$\Rightarrow$ Very sensitive to the gluon structure of the target!

- Heavy vector mesons:

  Heavy quark mass makes the process perturbative

  - Mass also low enough for saturation!

- Can be measured in:
  - DIS: Electron-ion collisions (HERA, EIC, . . . )
  - Ultra-peripheral collisions (LHC, . . . )

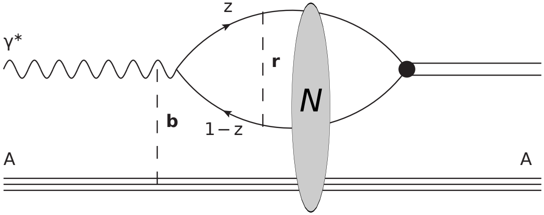


# Vector meson production at the leading order in the dipole picture

## Invariant amplitude for exclusive vector meson production

$$-i\mathcal{A}^{\lambda} = 2\int \mathrm{d}^2\mathbf{b}\,\mathrm{d}^2\mathbf{r}\,\frac{\mathrm{d}z}{4\pi} e^{-i\mathbf{b}\cdot\mathbf{\Delta}} \Psi_{\gamma^*}^{q\bar{q}}(\mathbf{r},z) N(\mathbf{r},\mathbf{b},x_{\mathbb{P}}) \Psi_{V}^{q\bar{q}*}(\mathbf{r},z), \qquad t = -\mathbf{\Delta}^2$$

- $\Psi_{\gamma^*}^{q\bar{q}}$: Photon light-cone wave function
- $N$: Dipole–target scattering amplitude
- $\Psi_{V}^{q\bar{q}}$: Vector meson light-cone wave function



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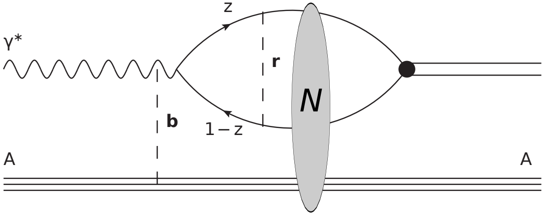
- Dependence on energy $W$ in the dipole amplitude:

$$x_{\mathbb{P}} = \frac{Q^2 + M_V^2 - t}{W^2 + Q^2 + m_N^2}$$

  - $Q^2 = 0$ for photoproduction



# Vector meson wave function

- Meson wave function is nonperturbative – has to be modeled
- Various different approaches:

  Nonrelativistic QCD, basis light-front quantization...
- We use the Boosted Gaussian that has been found to work well phenomenologically:

  Kowalski, Motyka, Watt (hep-ph/0606272)

$$\phi_\lambda(r, z) = \mathcal{N}_\lambda \exp\left( -\frac{m_Q^2 \mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m_Q^2 \mathcal{R}^2}{2} \right)$$

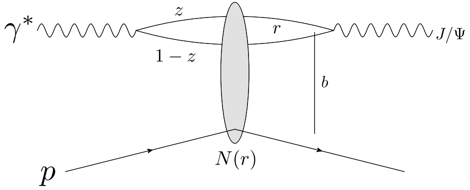
where $\mathcal{N}_\lambda$, $\mathcal{R}$ are parameters fixed by normalization and leptonic decay width

# Dipole amplitude $N$

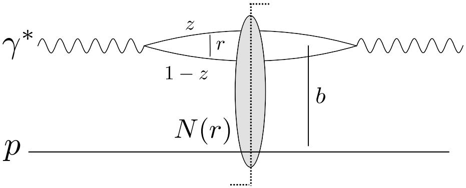
- Describes the interaction with the target
- High energy: **eikonal approximation**

$$N(\mathbf{x}, \mathbf{y}, x_{\mathbb{P}}) = 1 - \frac{1}{N_c} \left\langle \mathrm{Tr}\, V(\mathbf{x}) V^\dagger(\mathbf{y}) \right\rangle_{x_{\mathbb{P}}}$$

- Universal: appears in different processes
- Energy dependence given by a perturbative **evolution equation**




$$\sigma^{\gamma^* p \to Vp} \sim |N|^2$$




$$\sigma^{\gamma^* p} \sim N$$

# Estimating saturation effects

## Balitsky–Kovchegov equation

$$\frac{\partial}{\partial \log 1/x} N(\mathbf{x}_0, \mathbf{x}_1) = \frac{N_c \alpha_s}{2\pi^2} \int \mathrm{d}^2\mathbf{x}_2 \, \frac{\mathbf{x}_{01}^2}{\mathbf{x}_{20}^2 \mathbf{x}_{21}^2} \times [N(\mathbf{x}_0, \mathbf{x}_2) + N(\mathbf{x}_1, \mathbf{x}_2) - N(\mathbf{x}_0, \mathbf{x}_1) - N(\mathbf{x}_0, \mathbf{x}_2) N(\mathbf{x}_1, \mathbf{x}_2)]$$

- Saturation effects introduced by the nonlinear term in the BK equation
- Without nonlinear term: BFKL evolution

  $\Rightarrow$ Compare BK and BFKL evolutions to estimate saturation effects
- We also include the dependence on the impact parameter (usually neglected)
  - Neglecting it can lead to overestimating saturation effects JP et al. (2411.13533)

# Initial condition for the high-energy evolution

- Initial condition chosen as the impact-parameter-dependent McLerran–Venugopalan model JP et al. (2411.13533) $\mathbf{r} = \mathbf{x} - \mathbf{y}$, $\mathbf{b} = \frac{1}{2}(\mathbf{x} + \mathbf{y})$

$$N(\mathbf{x}, \mathbf{y}) = 1 - \exp\left( - \int \mathrm{d}^2\mathbf{z}\, \kappa\, T(\mathbf{z}) \Big[ K_0(m|\mathbf{x} - \mathbf{z}|) - K_0(m|\mathbf{y} - \mathbf{z}|) \Big]^2 \right)$$

  - $T(\mathbf{z})$ = the thickness function describing the shape of the target
  - $\kappa$ = constant describing the strength of the color field
  - $m$ = infrared regulator

**Proton**

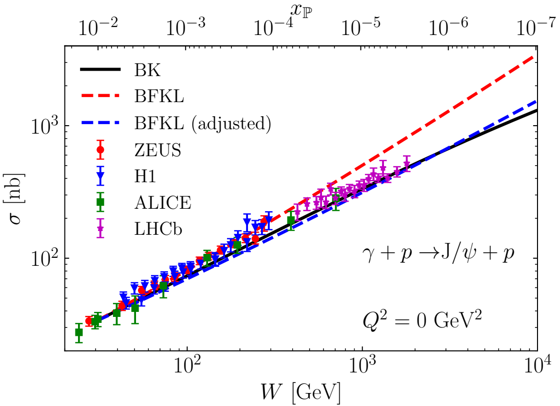
- $T(\mathbf{z})$ = Gaussian
- Parameters fixed by exclusive $\mathrm{J}/\psi$ production data

**Lead**

- From proton to nucleus: Change only $T(\mathbf{z})$
- $T(\mathbf{z})$ = Woods–Saxon

# Exclusive $J/\psi$ production: proton targets

- Slight difference between BFKL and BK in the slope
  - Can be compensated by adjusting $\alpha_s$ for BFKL
- Proton data described well by both BK and BFKL equations




JP, Royon (2411.14815)

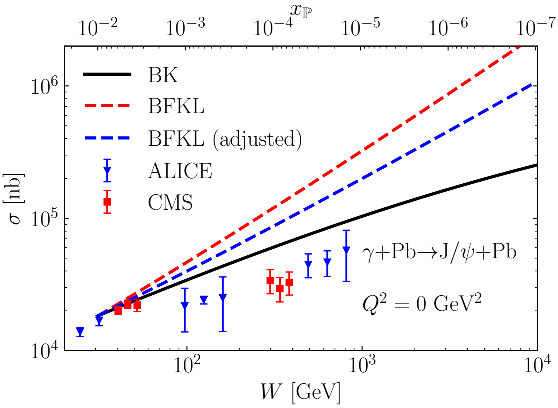
# Exclusive $J/\psi$ production: nuclear targets

- Fit the model to the proton data

  $\Rightarrow$ Predictions for heavy nuclei
- Differences between BK and BFKL:

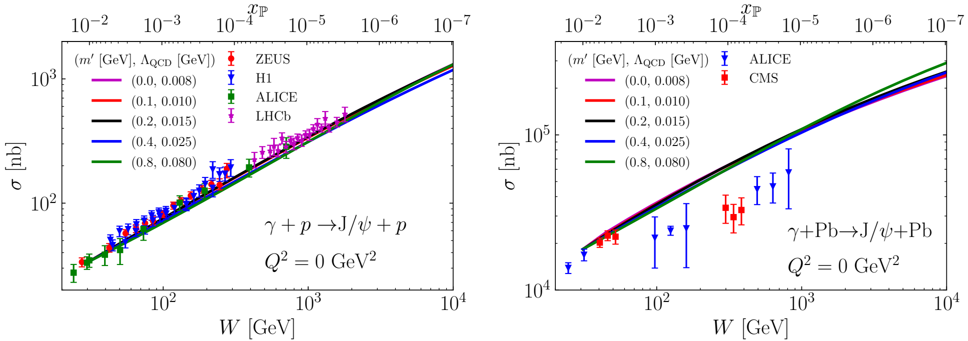
  a factor of 2 for $W \sim 1000$ GeV
- BFKL results linear as predicted
- BK describes the data much better
- Still not exact agreement:

  What could explain this?




JP, Royon (2411.14815)

# Exclusive J/$\psi$ production: nuclear targets




JP et al. (2411.13533)

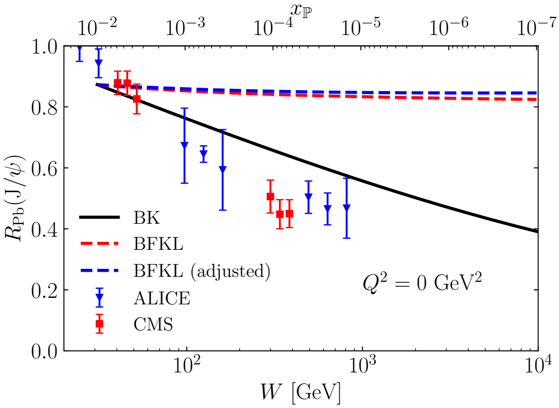
- Getting both proton and nuclear data to agree with the data is a very difficult problem...
- However: energy dependence **very robust** once fixed to the proton data!

# Exclusive $J/\psi$ production: nuclear suppression

- Nuclear suppresstion factor: $R_A = \sqrt{\sigma_A/\sigma_{\text{IA}}}$

  where $\sigma_{\text{IA}} = \frac{\mathrm{d}\sigma^p}{\mathrm{d}t}\Big|_{t=0} \times \int \mathrm{d}t\, |F_A(t)|^2$

  is the impulse approximation
- Without saturation: $R_A \approx 1$
- BFKL essentially constant
  - Linear evolution: energy dependence for protons and nuclei expected to be similar
  - Clear disagreement with the data
  - Saturation provides a natural explanation



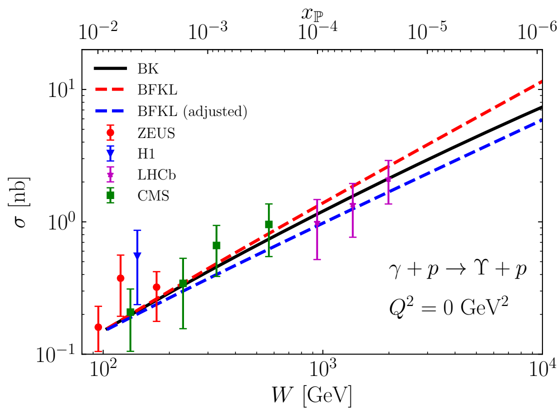

JP, Royon (2411.14815)

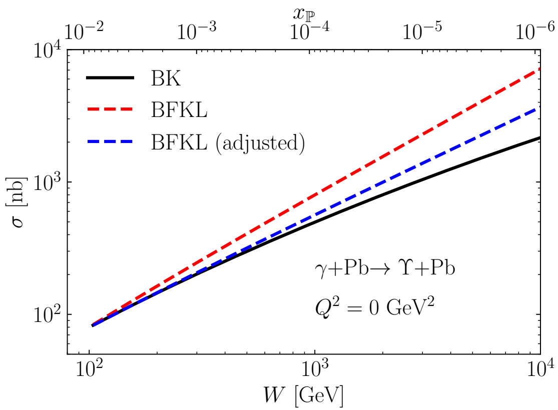
# Summary

- Gluon saturation expected at the high-energy limit
- Difficult to measure: need both a high energy and a low momentum scale
- Exclusive heavy vector meson photoproduction is a promising process
  - Diffractive process $\Rightarrow$ sensitive to the gluon density
  - Heavy quark mass $\Rightarrow$ large enough to be perturbative, small enough for saturation
- Compare linear BFKL and nonlinear BK evolution to estimate saturation effects
- Proton targets: no sign of saturation in the current data
- Pb targets: $\mathrm{J}/\psi$ **shows a clear preference for BK evolution**
  - Saturation effects already visible in the LHC data?
- Future prospects from the EIC: different target nuclei to understand nuclear effects

# Backup

# $\Upsilon$ production




- Saturation effects much smaller $\Rightarrow$ Not expecting sizable differences even at the LHC
- Follows from the large mass of $\Upsilon$

JP, Royon (2411.14815)